Interferometric Observations of the Quiet Sun at 20 and 25 MHz in May 2014

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Abstract We present the results of solar observations at 20 and 25 MHz with the *Ukrainian T-shaped Radio telescope of the second modification* (UTR-2) in the interferometric session from 27 May to 2 June 2014. In this case, the different baselines 225, 450, and 675 m between the sections of the east–west and north–south arms of UTR-2 were used. On 29 May 2014, strong sporadic radio emission consisting of Type III, Type II, and Type IV bursts was observed. On other days, there was no solar radio activity in the decameter range. We discuss the observation results of the quiet Sun. Fluxes and sizes of the Sun in east–west and north–south directions were measured. The average fluxes were 1050–1100 Jy and 1480–1570 Jy at 20 and 25 MHz, respectively. The angular sizes of the quiet Sun in equatorial and polar directions were 55′ and 49′ at 20 MHz and 50′ and 42′ at 25 MHz. The brightness temperatures of the radio emission were $T_b = 5.1 \times 10^5$ K and $T_b = 5.7 \times 10^5$ K at 20 and 25 MHz, respectively.

Keywords Corona, quiet · Corona, radio emission · Radio emission, quiet · Solar diameter

1. Introduction

The large size of the *Ukrainian T-shaped Radio telescope of the second modification* (UTR-2) allowed us to use it as an interferometer with baselines between its sections of

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up to 1.6 km in the north–south direction and up to 700 m in the east–west direction (Shepelev, 2015; Melnik *et al.*, 2017). Such interferometers provide the opportunity of defining the location of radio emission sources and their sizes at decameter wavelengths if they have sizes from some minutes to tens of minutes of arc. Such sizes are close to those of the quiet Sun (Aubier, Leblanc, and Boischot, 1971; Kundu, Erickson, and Gergely, 1977; Erickson *et al.*, 1977; Bhonsle, Sawant, and Degaonkar, 1979; Abranin and Bazelian, 1986; Thejappa and Kundu, 1992; Sastry, 1994; Subramanian, 2004; Ramesh *et al.*, 2006; Brazhenko *et al.*, 2012; Stanislavsky, Koval, and Konovalenko, 2013) and the sources of Type III bursts (Abranin *et al.*, 1976; Chen and Shawhan, 1978; Bhonsle, Sawant, and Degaonkar, 1979; Abranin *et al.*, 1980; Suzuki and Dulk, 1985; Melnik *et al.*, 2017), Type II bursts (Chen and Shawhan, 1978; Bhonsle, Sawant, and Degaonkar, 1979; Nelson and Melrose, 1985), and Type IV bursts (Gergely and Kundu, 1974; Chen and Shawhan, 1978) in the decameter range. Previously the sizes of these bursts were measured only occasionally at some discrete frequencies, but now we have the opportunity of observing radio emission of different bursts in the whole frequency band from 8 to 33 MHz on a regular basis.

During the period from 27 May to 2 June 2014, there was only one powerful coronal mass ejection (CME) on 29 May, accompanied by groups of Type III bursts, a Type II burst, and a Type IV burst, which were observed by UTR-2 and the *Ukrainian Radio interferometers of the Academy of Sciences* (URAN-2). The frequency and the temporal and spatial properties of these bursts will be discussed in a follow-up article. On other days, 27, 28, 30, 31 May, and 2 June, the activity of the Sun was low, and only separate weak Type III bursts were observed. This provided the opportunity of studying the radio emission of the quiet Sun before and after a CME.

In this article we present the results of interferometric observations of the quiet Sun at 20 and 25 MHz. The radio emission of the quiet Sun in the wide frequency band has been studied since the 1940s. Mainly it dealt with millimeter-, centimeter-, decameter-, and meter-wavelength bands. Observations of the quiet Sun at frequencies slightly higher and lower than 30 MHz were rare. Aubier, Leblanc, and Boischot (1971) were among the first to analyze radio emission of the quiet Sun at decameter wavelengths. Aubier, Leblanc, and Boischot (1971) observed the Sun with the Arecibo radio telescope and obtained fluxes of 3300 ± 500 Jy and 4000 ± 600 Jy at frequencies 29.3 and 36.9 MHz, respectively. The angular sizes of the Sun in the equatorial plane were $70' \pm 10'$ and $53' \pm 5'$; the brightness temperatures equaled 3.8×10^5 K and 5×10^5 K at these frequencies.

In May–June 1976 and April 1977, Kundu, Erickson, and Gergely (1977) observed the Sun by means of the radio telescope at Clark Lake at 26.3 MHz and found the fluxes, sizes, and brightness temperatures of the quiet-Sun radio emission to be equal to $1.6 \pm 0.4 \times 10^3$ Jy, $56.6' \pm 6'$, and 4.7×10^5 K, respectively. Observations of the quiet Sun performed by Erickson *et al.* (1977) with this radio telescope in July–August 1977 gave fluxes $< 1.1 \times 10^3$ Jy, $1.5 \pm 0.3 \times 10^3$ Jy, and $1.2 \pm 0.2 \times 10^3$ Jy, sizes $55'$, $50'$, and $48'$, and brightness temperatures 5×10^5 K, 4.4×10^5 K, and 2.6×10^5 K at frequencies 19, 25.8, and 30.9 MHz, respectively. The average angular sizes of the quiet Sun in east–west and north–south directions obtained with the radio heliograph at Clark Lake in September 1986 (Thejappa and Kundu, 1992) equaled $64'$ and $53'$, while the brightness temperatures varied from 0.5×10^5 K to 2.5×10^5 K at 38.5 MHz.

Observing the Sun with the UTR-2 heliograph in 1976–1977, Abranin and Bazelian (1986) found lower fluxes of 770–990 Jy and sizes $56'$ – $58'$ at a frequency of 25 MHz.

At a frequency of 34.5 MHz, the quiet Sun was studied many times with the radio telescope in Gauribidanur (India). Observations in August 1983 (Sastry, 1994) showed that the diameter of the quiet Sun was 3 – $4 R_{\odot}$ and the brightness temperature changed from day to

day in the range $1 \times 10^5 - 7 \times 10^5$ K. Subramanian (2004) observed the angular size in the equatorial plane from $39'$ to $66'$ and brightness temperature from 1×10^5 K to 4.5×10^5 K during the observations in June–July 1986 and in May–June 1987.

During the last solar minimum (2008–2009), the radio emission of the quiet Sun was observed with the radio telescope URAN-2 (Poltava, Ukraine) (Brazhenko *et al.*, 2012). The fluxes obtained were relatively low: 710 and 870 Jy in 2008 and 700 and 860 Jy in 2009 at frequencies 20 and 25 MHz, respectively. In September 2010, the quiet Sun was observed by the UTR-2 radio heliograph (Stanislavsky, Koval, and Konovalenko, 2013), which gave fluxes of 763 and 1094 Jy and (E–W) $\times$ (N–S) sizes of $60' \times 50'$ and $58' \times 42'$ for the same set of frequencies.

For the periods of a deep minimum in solar activity and for the years of its increasing phase, the measured fluxes, sizes, and brightness temperatures differ significantly. The parameters of the quiet Sun are non-stationary. It is of interest to analyze in what way the sizes of the Sun and its brightness temperatures vary during the 11-year cycle and how these parameters are affected by such strong phenomena as CMEs, which disturb the solar corona. For this reason, regular observations of the Sun with UTR-2 in interferometric mode seem to be very promising because of its high sensitivity, large sizes, and wide working frequency range.

In this article we consider the first results obtained in solar observations with UTR-2 in the interferometric regime with different baselines in east–west and north–south directions at frequencies 20 and 25 MHz, which are aimed at obtaining reliable data for the time before and after the CME that occurred on 29 May 2014.

2. Radio Telescopes

The UTR-2 is situated near Kharkiv (Ukraine). This is a T-shape antenna array with two arms extending east–west and north–south. The arm extending east–west has a length of 900 m and a width of 39.3 m and consists of 600 dipoles (Figure 1). The arm extending north–south with a length of 1860 m and a width of 53 m consists of 1440 dipoles (Braude *et al.*, 1978; Konovalenko *et al.*, 2016). All dipoles are grouped into four (east–west) and eight (north–south) sections, which can be operated separately. The beam of each section is $4^\circ \times 15^\circ$ and the beam of the whole antenna is $25' \times 25'$ at a frequency 25 MHz. The total area of the radio telescope comprises about 140 000 m². The working frequency band of the UTR-2 is 8–33 MHz. The spectral analyzers for the interferometric observations are operating at frequencies of 20 and 25 MHz with a frequency width of 250 kHz.

Observations in the interferometric regime with UTR-2 were supported by observations of the URAN-2. The URAN-2 is located near Poltava (Ukraine) (Brazhenko *et al.*, 2005).

Figure 1 Layout of UTR-2.

Figure 2 Dependencies of visibility functions for Gaussian sources of different sizes *versus* the baseline of the UTR-2 interferometers east–west (squares) and north–south (triangles) at 25 MHz.

This is a rectangular array with an effective area of 28,000 m² operating in the frequency band of 8–33 MHz. This antenna array has a size of 238 m east–west and 118 m north–south and a beam size of $3.5^\circ \times 7^\circ$ at a frequency of 20 MHz. The signals are recorded with a digital spectrum analyzer (DSPz) (Ryabov *et al.*, 2010), which allows us to carry out observations with a time–frequency resolution of 4 kHz–100 ms and a dynamic range of 90 dB in the frequency band of 8–32 MHz.

Because sections of UTR-2 have independent outputs, the interferometers can be shaped with different baselines. We used baselines between neighboring sections (225 m), over one section (450 m), and over two sections (675 m) of the east–west and north–south arms.

The angular size of a radio-emission source is defined by the analysis of the visibility function (Thompson, Moran, and Swenson, 2001). Figure 2 shows visibility functions $[\gamma]$ of sources with different sizes for interferometers with different baselines $[L]$ at 25 MHz according to the equation

$$\gamma = \exp \left[- \left(\frac{\pi \theta L}{2\lambda \sqrt{\ln 2}} \right)^2 \right], \quad (1)$$

where θ is the half-flux angular size and λ is the wavelength at which observations are carried out. Sources with angular sizes from some minutes of arc to tens of arcminutes can be measured with the interferometers of UTR-2. Since the size of the quiet Sun at decameter wavelengths is tens of minutes of arc and sources of bursts are smaller in size than the quiet Sun (Bhonsle, Sawant, and Degaonkar, 1979), such interferometers can be effective for measurements of sizes in the wide frequency band from 8 to 32 MHz.

3. Observations

Observations were carried out from 27 May to 2 June 2014 with ten-minute scans at angles of $\pm$ two hours from culmination. The source 3C144 was used for calibration. This source had the same declination and one-hour separation in right ascension from the Sun in the observing period, so that after every two solar scans, the interferometer beam was directed to 3C144.

As described above, these observations were also supported by observations with URAN-2 in the frequency band of 8–32 MHz. The dynamic spectra of solar radio emission on the day before and the day after the CME are presented in Figure 3. On these days, there was no important radio activity in the decameter range. At the same time, there were some active regions on the solar disk (Figure 4). The CME on 29 May 2014 was ejected in the northeast direction and was accompanied by groups of Type III, a Type II, and a Type IV

Figure 3 Dynamic radio emission spectra of the Sun on 28 May (a) and 30 May (b) 2014 in the frequency band of 8–33 MHz according to URAN-2.

Figure 4 Solar disk on 27 May and 30 May 2014 according to SOHO (obtained with the *Extreme ultraviolet Imaging Telescope* at 304 Å).

bursts that were observed by both UTR-2 and URAN-2. Their properties, including the sizes of their sources and their locations, will be presented in the next article. Here we discuss the radio emission fluxes of the quiet Sun and its sizes before and after the CME.

Solar radio emission in the period 27–30 May 2014 was observed with the interferometer consisting of the east–west sections with baselines of 225, 450, and 675 m. In the period from 31 May to 2 June, the interferometer consisting of the north–south sections was used with the same baselines. Thus the sizes of the quiet Sun in the equatorial and polar directions

Figure 5 Visibility functions of the quiet Sun in east–west (27, 28 and 30 May) (a and b) and north–south (31 May, 2 June) (c and d) directions at 20 and 25 MHz.

Table 1 Sizes and fluxes of the quiet Sun at 20 and 25 MHz according to observations on 27 May – 2 June 2014.

Frequency [MHz]	E–W		N–S	
	size [min]	flux [Jy]	size [min]	flux [Jy]
20	55 ± 4	1050 ± 150	49 ± 3	1100 ± 230
25	50 ± 3	1480 ± 130	42 ± 2	1570 ± 190

were measured on 27–30 May and from 31 May to 2 June, correspondingly. Average visibilities were derived from the scans without interference and close to Noon. These values did not change significantly from day to day, and we present the average visibilities for 27, 28, 30 May (east–west) and 31 May, 2 June (north–south) in Figure 5.

We assumed Gaussian distributions of the-quiet Sun brightness and derived the curves from the observational data according to Equation 1. The corresponding angular sizes of the quiet Sun in east–west and north–south directions at frequencies of 20 and 25 MHz are summarized in Table 1. These sizes are close to those obtained by Kundu, Erickson, and Gergely (1977) in interferometric observations with the radio telescope at Clark Lake, although those observations were carried out at minimum solar activity. At the same time, heliograph measurements (Abranin and Bazelian, 1986; Stanislavsky, Koval, and Konovalenko, 2013) gave slightly larger sizes in both directions. A determination of the sizes obtained with the method in which the radio source passes through the antenna beam as was reported by Aubier, Leblanc, and Boisshot (1971), Sastry (1994), Subramanian (2004), and Ramesh *et al.* (2006) probably gave larger sizes. The difference in sizes may be connected with their dependencies on solar activity. Thus regular observations with different methods are required to define the sizes of the Sun as a function of time and solar activity. Under the

Figure 6 Fluxes of the quiet Sun at frequencies of 20 and 25 MHz from 27 May to 2 June 2014.

assumption that the sizes of the quiet Sun did not change significantly during the week of our observations, its compression factor (polar to equatorial size ratio) was 0.89 and 0.84 at 20 and 25 MHz, respectively. These values are close to those obtained by van de Hulst (1947). The measured fluxes of the quiet Sun were calibrated on the source 3C144, whose flux is well known and equals 3000 Jy at a frequency of 25 MHz (Bobeiko *et al.*, 1979). Observations were carried out in such a way that during 20 minutes (two scans), the interferometer beam was pointed at the Sun, and after this, it followed the source 3C144. The average flux per day was defined on the scan near local Noon. Figure 6 shows that the fluxes before and after the CME were practically the same.

The measured fluxes were comparable to the fluxes obtained by Erickson *et al.* (1977) at the radio telescope at Clark Lake and are significantly lower than those from observations by Arecibo (Aubier, Leblanc, and Boischot, 1971) and significantly higher than fluxes registered with UTR-2 and URAN-2 (Abranin and Bazelian, 1986; Brazhenko *et al.*, 2012; Stanislavsky, Koval, and Konovalenko, 2013). In the last cases, observations were conducted at solar activity minimum, so that the difference seems understandable.

4. Discussion

The brightness temperature of the quiet Sun is defined by the equation (Aubier, Leblanc, and Boischot, 1971)

$$T_b = 5.5 \times 10^{29} \frac{\lambda^2 S}{\theta_W \theta_N}, \quad (2)$$

where S is the flux [$\text{Wm}^{-2} \text{Hz}^{-1}$], θ_W , θ_N are diameters [minutes] in equatorial and polar directions, and λ is the wavelength [m]. Using the average fluxes and sizes obtained at frequencies 20 and 25 MHz, we obtain for brightness temperatures of the quiet Sun $T_b = 5.1 \times 10^5 \text{ K}$ and $T_b = 5.7 \times 10^5 \text{ K}$ at these frequencies. These values, as well as the temperatures derived by other authors, are noticeably lower than the temperature of the coronal plasma, which is typically assumed to be equal to $T_c = 10^6 \text{ K}$. This difference can be explained by scattering of electromagnetic waves on the density inhomogeneity of coronal plasma. Such a supposition was stated first by Aubier, Leblanc, and Boischot (1971) and then was discussed many times (Abranin and Bazelian, 1986; Thejappa and Kundu, 1992; Subramanian, 2004; Thejappa and MacDowall, 2008). Thejappa and MacDowall (2008) recently studied in detail the influence of processes of scattering in the solar corona on brightness temperatures and

Figure 7 Baumbach–Allen (dashed) and Newkirk (solid) models and radii of the quiet Sun according to the observations we presented.

sizes of the quiet Sun at low frequencies by the Monte Carlo method, assuming Kolmogorov and flat spectra of random density fluctuations. They obtained that brightness temperatures of the quiet Sun at 30 MHz can be as low as 1.5×10^5 – 4.5×10^5 K and can be even much lower at lower frequencies. Thus our brightness temperatures 5 – 6×10^5 K can be explained by scattering in the solar corona, as stated by other authors (Aubier, Leblanc, and Boisshot, 1971; Abranin and Bazelian, 1986; Thejappa and Kundu, 1992). We mention that another point of view is also possible (Sastry, 1994; Subramanian, 2004; Ramesh *et al.*, 2006), according to which a high level of density fluctuations leads to very large sizes of the quiet Sun. Thejappa and MacDowall (2008) used a Monte Carlo method and found that the sizes that they obtained were close to the observed sizes, however. We consider that the choice of the level of density fluctuations, their inner and outer scales, and their degree of asymmetry can give reasonable values of brightness temperatures and sizes at different frequencies and vice versa. We plan to observe the quiet Sun in the whole working frequency band of UTR-2, 8–32 MHz, and to determine the parameters of the density fluctuations in the solar corona at heights 0.5 – $2 R_\odot$ using different methods including Monte Carlo method. Concerning the sizes obtained, it is worth pointing out that the radii of the quiet Sun are close to the distances from the Sun at which the local plasma frequency is equal to the corresponding observed frequency of radio emission in the Baumbach–Allen model (Allen, 1947) (Figure 7). At the same time, we see (Figure 7) that observational points are situated notably below the Newkirk model $n(r) = n_0 10^{4.32 R_\odot/r}$ ($n_0 = 4.2 \times 10^4 \text{ cm}^{-3}$, and r is the distance from the Sun) (Newkirk, 1961), which agreed with Mann’s model (Mann *et al.*, 1999) for the coronal plasma temperature $T_e = 1.9 \times 10^6$ K.

5. Conclusion

Interferometric observations of the quiet Sun with UTR-2 showed that they can be used to determine quiet-Sun parameters such as fluxes, sizes, and brightness temperatures at heights 0.5 – $2 R_\odot$. From this point of view, it is of current interest to regularly observe the quiet Sun in the decameter range. During the first observations in the interferometric session at UTR-2, we found that

- a Gaussian distribution of the quiet Sun intensity is a good approximation;
- the brightness temperatures of the quiet Sun are $T_b = 5.1 \times 10^5$ K and $T_b = 5.7 \times 10^5$ K at 20 and 25 MHz, correspondingly, and they are lower than the temperature of the coronal plasma;
- the obtained radii of the quiet Sun at 20 and 25 MHz are close to distances from the Sun of corresponding local plasma frequencies in the Baumbach–Allen solar corona;

- the compression factor of the quiet Sun is about 0.85–0.9 in the decameter range; and
- the radio fluxes of the quiet Sun at 20 and 25 MHz are practically the same on the days before and after a CME.

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Conflict of interest The authors declare that they have no conflicts of interest.

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